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14. ABSTRACT
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INITIAL RESULTS FROM THE DEMONSTRATION AND ANALYSIS OF REUSABLE NANOSAT LAUNCH VEHICLE OPERATIONS*

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ABSTRACT

Flight testing of prototype reusable launch vehicles (RLVs) has declined significantly since a period in the mid-1990s that was marked by ambitious projects but uneven results. Consequently, a new program has been established with the objective of investigating RLV-type fast turn-around flight operations. Major distinctions from these earlier efforts include the use of a smaller class of vehicles and payloads, along with an initial emphasis on operations as opposed to advanced technologies. This focus on a hybrid-type (reusable first stage and expendable second stage) "nanosat launch vehicle" (NLV) that ultimately could deliver 10 kg to low Earth orbit has already produced tangible results. These include initial operational capability of a new prototype vehicle just six months after project start, two flights of this vehicle within 3.5 hours, a total of four flights within an eleven month period, pathfinding operations from a new launch site and the manifesting of numerous technology and academic experiments. Lessons learned from this first round of demonstration and analysis are now guiding the development of several next-generation prototype reusable NLVs that will enter flight testing later this year.

INTRODUCTION

After a period of renewed interest and support in the mid and late 1990s, flight-based test and evaluation of reusable launch vehicles (RLVs) in the United States stagnated as technical integration difficulties arose and launch vehicle research priorities shifted to other missions and concepts. An attempt is now underway to re-invigorate such RLV flight research by adopting the incremental approach to vehicle development and phased testing that characterized the successful Delta Clipper program (DC-X/XA), which featured a prototype vertical take-off/vertical RLV. This new program is initially focusing on the operational aspects of and metrics associated with conducting responsive, fast turn-around flights using prototype RLVs that are based on the first stage of a proposed hybrid-type (reusable first stage, expendable second stage) nanosat launch vehicle (NLV).

The first such test vehicle - the Prospector 7 (P-7) - was developed and entered flight just six months after authority to proceed was given under a Phase I Small Business Innovation Research (SBIR) contract from the Air Force Research Laboratory's Propulsion Directorate to a team lead by Garvey Spacecraft Corporation (GSC) and research partner California State University, Long Beach (CSULB). The GSC/CSULB team was able to move quickly by leveraging experiences from previous internally-sponsored NLV-related flight projects. This current effort has now transitioned into a Phase II SBIR that involves the development of a next-generation prototype reusable NLV first stage, with the Space and Missile Systems Center (SMC) and The Aerospace Corporation also making key contributions.

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* This effort was performed under AFFTC contract numbers FA9300-05-M-3010 and FA9300-06-0009 with the Air Force Research Laboratory / Propulsion Directorate.

PROSPECTOR 7 BACKGROUND AND HISTORY

VEHICLE DESIGN AND DEVELOPMENT

Figure 1 presents the P-7 vehicle concept as envisioned at the start of the program. The propulsion system features liquid oxygen and ethanol propellants with tank ullage pressurization for the feed system and a 1200 lbf-thrust engine with a pintle injector and ablative thrust chamber. The P-7 is passively guided, with recovery implemented through a redundant pair of on-board accelerometers that control the initial deployment of a drogue parachute at apogee and then later a pilot parachute that in turn extracts a main parachute from the side of the first stage.

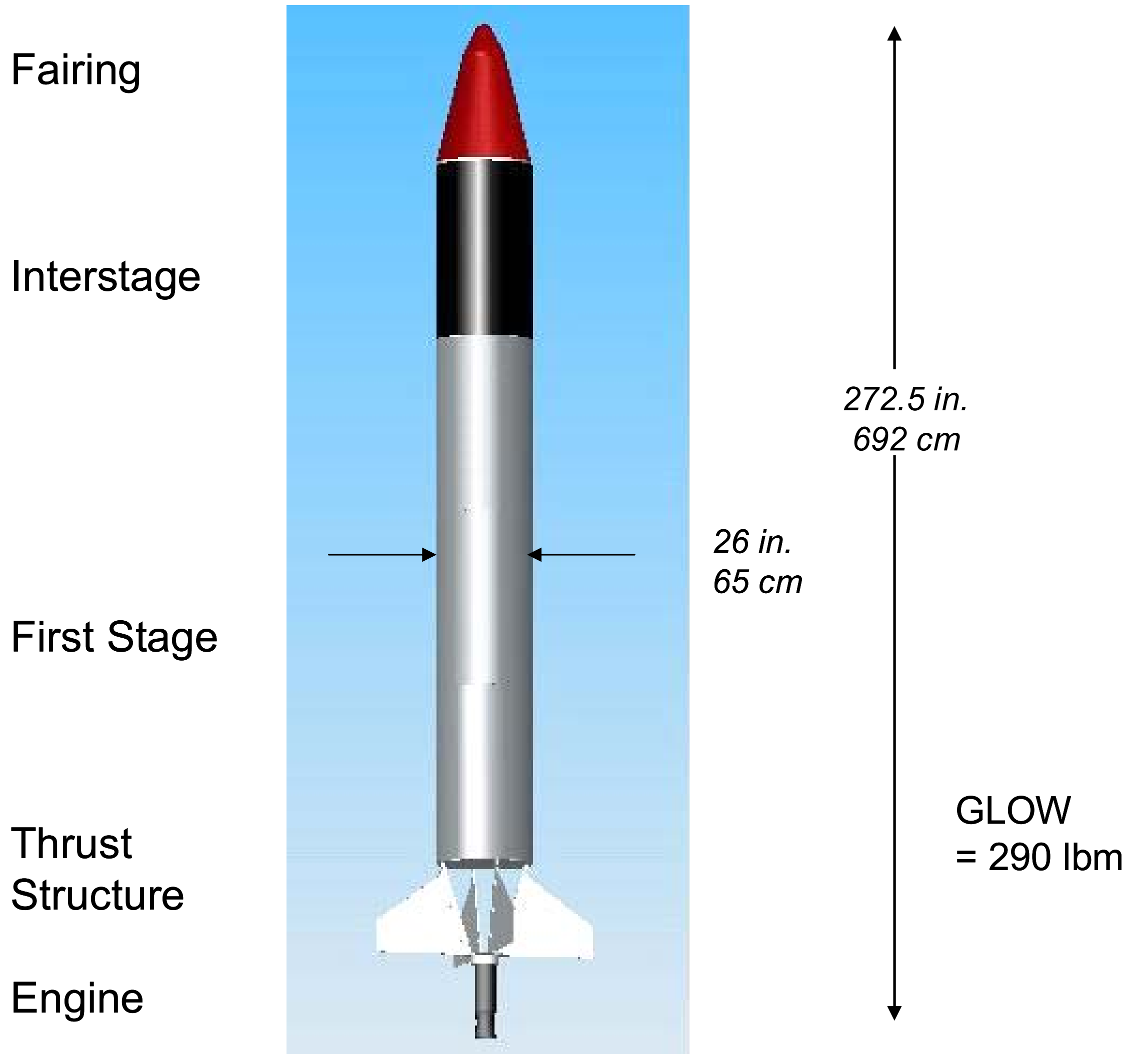


Figure 1. Original P-7 Concept

The P-7 lands fairing-first, with both the fairing and interstage absorbing the initial shock so as to minimize damage to the reusable first stage. For rapid turn-around operations, the fairing and interstage are removed and replaced in the field and then subsequently refurbished back in the CSULB lab for reuse in future flights. After this initial impact, the vehicle then pivots until the aft end of the first stage reaches the surface, at which point the fins making contact and their associated struts deform to absorb the remaining kinetic energy. These and the engine chamber are replaced at the same time that the servicing activities at the forward end of the stage are underway.

The extremely short development cycle for the P-7 was possible in part because of heritage with previous test vehicles, most notably the Prospector 5 and 6.[1] This design maturity was also reflected in the relatively stable mass estimates during development (Figure 2). A second factor was that performance goals were set conservatively (nominal peak altitude for this prototype was 5 kft above ground level) to establish a high degree of confidence in meeting the aggressive cost and schedule objectives. A third consideration was that assembly, integration and checkout took place in the Aerospace System Integration Lab on the CSULB campus, with the additional benefit of extensive student participation.

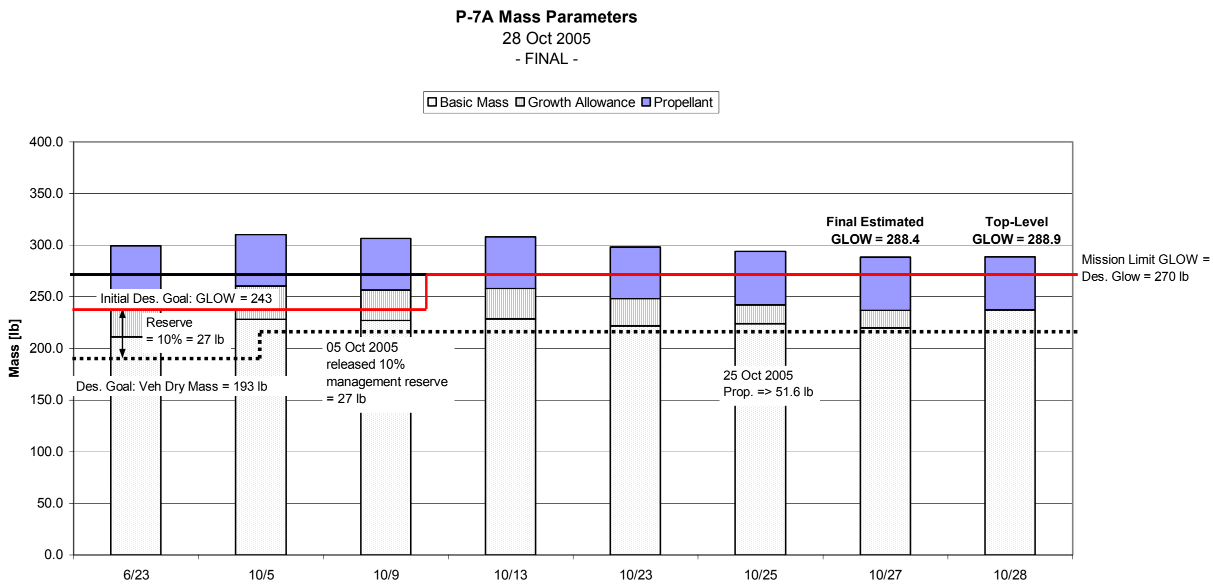
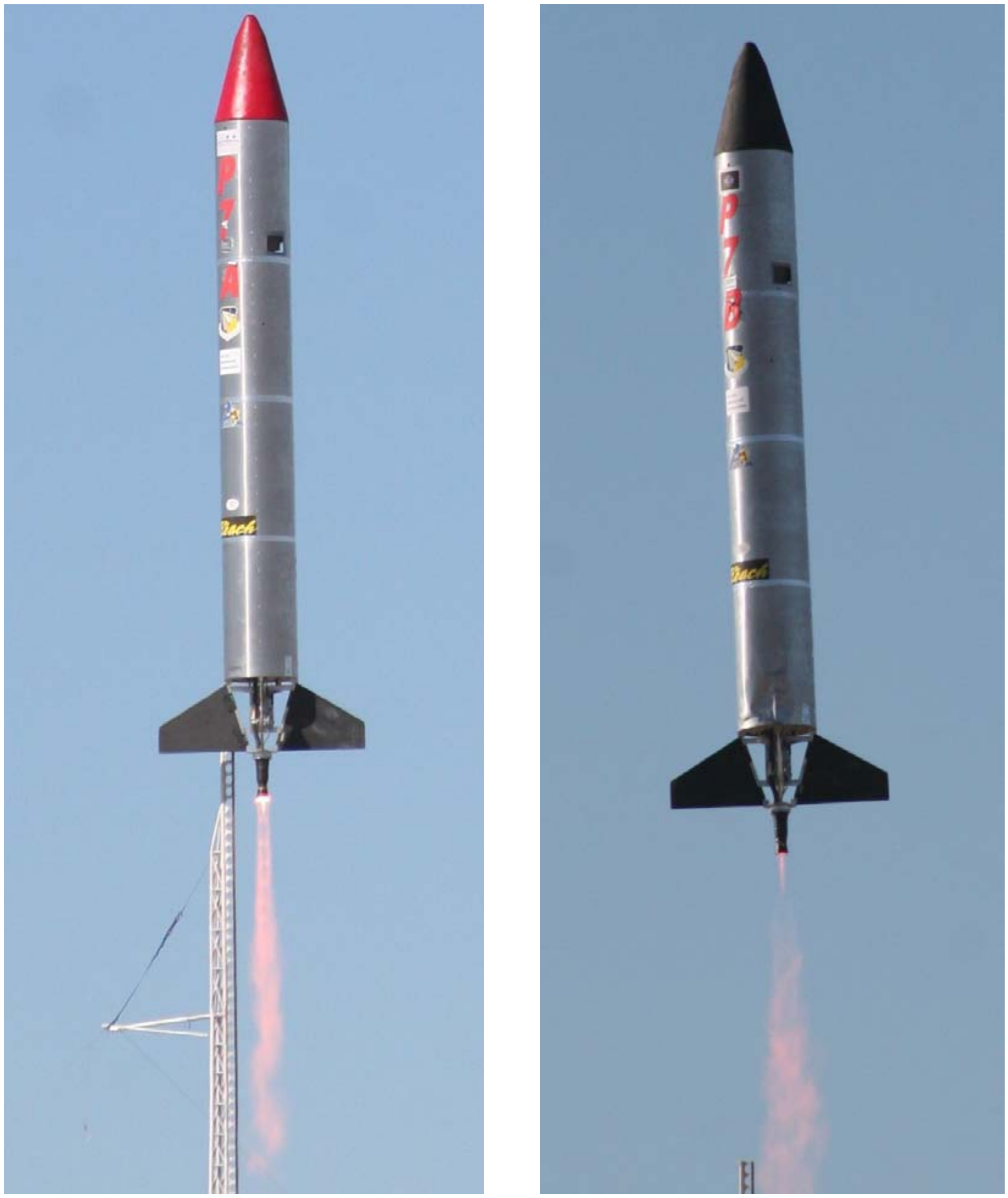


Figure 2. The Maturity of the Basic P-7 Configuration was Reflected in Stable Mass Esimates Throughout Development

P-7A/B: RLV FAST-TURNAROUND FLIGHT DEMONSTRATIONS

The primary goal of the Phase I effort was to conduct two missions with the P-7 vehicle (labeled the P-7A and P-7B for the first and second flights, respectively) within a 24-hour period, while quantifying and evaluating operational parameters. This was accomplished successfully on the first attempt, with turn-around between flights actually requiring only 3.5 hours (Figure 3). Equally noteworthy was that the operations occurred on a empty dry lake bed in the Mojave desert (Figure 4) with absolutely no facilities, after just 18 hours of on-site preparations. Total on-site time was less than one day. The only major issue that arose came after the first flight, for which helium consumption had been higher than anticipated. A decision was made to continue with the second flight, using nitrogen as a substitute, despite the risk of possible performance impacts. This did indeed occur, but the P-7b was still able to achieve sufficient altitude to accomplish the mission goals and then perform a nominal landing (Figure 5).

In addition to the RLV-focused demonstrations, the P-7 also manifested several academic payloads from CSULB, Montana State University and Cal Poly San Luis Obispo. The latter consisted of a prototype deployment system for CubeSat-class payloads that has direct traceability to possible future NLV payload accomodations.[2]



P-7A P-7B

Figure 3. First Two Flights of the Prospector 7

Figure 4.P-7 Turn Around Operations Between First and Second Flight

Figure 5. P-7B Just Prior to Landing

P-7C: LAUNCH HARDWARE TRACKER FLIGHT DEMONSTRATION

Post-flight inspection after the RLV rapid turn-around demonstration confirmed that the P-7 was available for continued flight testing with minimal maintenance and that most of the removeable hardware from the first two flights (i.e. fairings, interstages and fins) could also be refurbished and put back into flight. Taking advantage of this opportunity, SMC and The Aerospace Corporation jointly engaged AFRL and the GSC/CSULB team to conduct a third flight with the P-7, this time for a true operational RLV mission with a technology payload. Specifically, The Aerospace Corporation used the P-7C to manifest an engineering prototype of a proposed Reentry Breakup Recorder (REBR). By enabling the use of existing lab and commercially available hardware, this Launch Hardware Tracker experiment provided the REBR team a low cost, early opportunity to test and evaluate the core GPS tracking and Iridium telemetry functions in an actual launch environment (Figure 6).[3] In parallel, SMC supported a number of tasks that established the foundation for future ORS-oriented pathfinder missions at other launch sites. The successful recovery of the P-7 along with the experiment again created the possibility of more flight testing at a fraction of the cost that would otherwise be associated with expendable systems.

Figure 6. The P-7C Conducting an Operational RLV Mission for SMC and The Aerospace Corporation

P-7D: ORS PATHFINDER FLIGHT TEST AT SAN NICOLAS ISLAND

The fourth and final flight of the P-7 was conducted under the Phase II follow-on SBIR project that got underway in mid-2006. It served as a pathfinder for ORS operations at the Navy's San Nicolas Island within the Sea Range off the southern California coast (Figure 7).[4] This campaign identified numerous issues and candidate solutions for future small launch vehicles that may deploy from non-traditional launch sites. By creatively adapting to range requirements and resources, the team was able to get into flight less than three months from the time that the SMC sponsors gave the go ahead to proceed. Also worth noting is that the mission took place only two days after the launch team arrived on island, within 10 minutes of the start of the first launch window on the first and only countdown. However, the major programmatic compromise needed to achieve this schedule performance was the deletion very late in the planning process of vehicle recovery, thereby making this the P-7's final flight.

Figure 7. The P-7D Pathfinding ORS Launch Operations at San Nicolas Island After Just Three Months of Mission Planning and Range Coordination

RESULTS AND DISCUSSION

The series of four flight tests within eleven months with a single vehicle, two on the same day, constitute the most tangible results so far from this reusable NLV research initiative. In addition, this focus on RLV turn-around operations has caused the GSC/CSULB team to evolve our approach to defining and tracking launch operations. On previous flight projects, the percentage of reusable versus replaceable / expendable hardware was of no relevance, while neither process times or manpower requirements had been treated as high-priority metrics.

Featuring data from the P-7A to P-7B turn-around operation, Table 1 reflects a first attempt to assess and quantify the amount of "replaceable" hardware associated with the P-7 kind of configuration for a reusable NLV first stage. The value of 16.9% was slightly under the predicted 18.3%. Potentially more significant from a life cycle cost perspective is that when post-flight refurbishment of the removed hardware is included for a sustaining operation (i.e. - repair of the fairings, interstages and fins), the actual amount of expended hardware falls to under 5%.

Table 1. Metrics On Replaced Components Between the P-7A and P-7B Flights

Baselined Components Requiring Replacement	**Baselined Mass of Replaced Components*** [kg / lbm]	**Actual Mass of Replaced Components** [kg / lbm]	**Components Actually Requiring Replacement**
engine (except pintle injector element, which is reused)	4.5 / 9.9	4.5 / 9.9	engine
fins (x2)	3.0 / 6.6	1.5 / 3.3	fins (x1)*
thrust structure struts (x2) (brackets not included)	0.7 / 1.6	0.4 / 0.8	struts (x1)
		0.7 / 1.5	first stage forward mating ring
interstage	8.5 / 18.7	8.5 / 18.7	interstage*
payload fairing	3.0 / 6.6	3.0 / 6.6	payload fairing*
TOTAL =	**19.7 / 43.4** **18.3% of final dry mass estimate****	**18.6 / 40.0** **16.9% of final dry mass estimate****	

* *these components were actually reused on subsequent flights, giving a final expended mass of 4.8% for this flight*

** *final vehicle dry mass estimate, with payloads, was 237.3 lb*

Table 2 presents the pre-flight estimates and actual times required for turn-around operations between the P-7A and -7B flights. As with the hardware removal and replacement metrics, the pre-flight forecast (4 hr 15 min) proved to be conservative compared to the actual time needed (3 hr 26 min).

Table 2. Metrics on Turn-Around Operations Between the P-7A and P-7B Flights

	Local Time [h:min]	Elapsed Time After Start of Recovery and Turn Around Ops [h:min]	Task Duration [h:min]	Pre-Launch Estimated Duration [h:min]	Active Personnel	Estimated Manhours
P-7A launch	12:25					
P-7A landing	12:27					
P-7A POST-LANDING						
post-landing recovery ops - start	**12:27**		0:22	1:00	2	2:00
post-landing recovery ops - completed	12:49	0:22				
vehicle return to launch site - start	12:49	0:22	0:10	0:30	4	2:00
vehicle return to launch site - completed	12:59	0:32				
P-7A/7B REFURBISHMENT						
vehicle inspection, refurbishment and conversion to P-7B configuration - start	12:59	0:32	1:18	1:15	8	10:00
vehicle inspection, refurbishment and conversion to P-7B configuration - completed	14:17	1:50				
Flight Readiness Review - start	14:17	1:50	0:03	0:15	8	2:00
Flight Readiness Review - completed	14:20	1:53				
P-7 LAUNCH OPS						
load, prep vehicle on launch rail - start	14:20	1:53	1:01	0:30	8	4:00
load, prep vehicle on launch rail - completed	15:21	2:54				
ethanol loading - start	15:21	2:54	0:09	0:30	4	2:00
ethanol loading - completed	15:30	3:03				
LOX loading - start	15:30	3:03	0:15			
LOX loading - completed	15:45	3:18				
Conduct air and ground safety check; enter terminal count	15:45	3:18	0:08	0:15	4	1:00
P-7B launch	15:53	**3:26**				
TOTALS			**3:26**	**4:15**		**23:00**

Because of the low design fidelity of the P-7 with an expected high performance NLV, there is a limit to the precision of any extrapolations made from this first data set to that for an operational system. The key conclusion is that the turn-around was conducted in hours, as opposed to days, weeks, months or years. Furthermore, the exercise of defining and refining RLV servicing processes is already paying dividends in subsequent flight tests, as best demonstrated by the efficient P-7D launch campaign at SNI. As noted in the Future Works section below, updating these turn-around metrics is a primary goal for the first flights of the next-generation Prospector 9 RLV now in development.

SUMMARY AND CONCLUSIONS

The early success of the reusable NLV flight test program is validating the premise that valuable operational and technology research results can be achieved with small-scale prototype RLVs. In terms of spirit, personnel, design and operational practices this effort traces directly back to the pioneering DC-X/XA program of the mid-1990s. As a corollary benefit, the nanosat payload community is already taking advantage of the expanded number of manifest opportunities, perhaps best illustrated by the sponsorship of the operational P-7C RLV mission by the primary payload provider. The challenge going forward is to

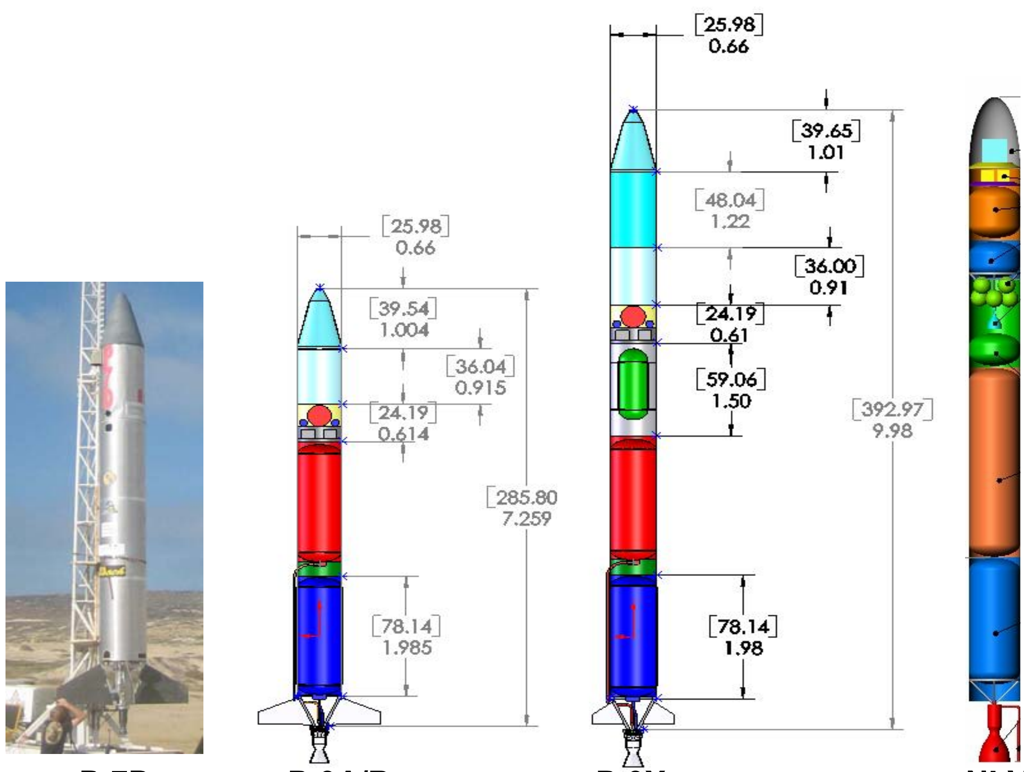
maintain this level of responsiveness and utility as both vehicle performance and operational fidelity to orbital missions increase.

FUTURE WORK

Since the completion of the final P-7 flight in September 2006, research priority has shifted to developing the next-generation Prospector 9 (P-9) that will enable significant expansion of the research envelopes for both RLV rapid turn-around and ORS-type flight operations. The P-9 configuration incorporates the following enhancements that promise to produce a magnitude improvement in performance:

- full-scale NLV first stage engine (4,500 lbf-thrust)
- full-scale propellant tanks
- regulated tank pressurization system
- thrust vector control

As shown in Figure 8, P-9 development is taking the same incremental approach that has characterized previous GSC/CSULB projects. The initial P-9A/B configuration with the 4,500 lbf-thrust engine and full-scale propellant tanks is intended to enable the next round of RLV rapid turn-around flight demonstrations in mid-2007. Its subsequent conversion into the high performance P-9X with a regulated propellant tank pressurization system and closed-loop thrust vector control will then be followed by a return to SNI for an attempt at a high altitude (20 to 50 mile) ORS pathfinder mission in early 2008. The first static fire test of the 4,500 lbf-thrust engine (Figure 9) represents the most recent milestone towards reaching initial operational capability later this year.



P-7D **P-9A/B** **P-9X** **NLV**

(approximate scaling)

Figure 8. The P-9A/B and P-9X Vehicles Represent the Next Incremental Steps in the Development Path to an Operational, Reusable NLV

Figure 9. First Static Fire Test of a Prototype 4,500 lbf-thrust NLV First Stage Engine (Feb 2007)

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3. Garvey, J. and D. Garza, " Responsive Flight Testing of a Launch Hardware Tracker Experiment Using a Prototype Nanosat Launch Vehicle," paper no. SSC06-IX-2, 20th Annual AIAA/USU Conference on Small Satellites, Logan, Utah, 17 August 2005.

4. Naval Air Warfare Center Weapons Division, **Sea Range User's Handbook**, dated October 1996.

Garvey Spacecraft Corporation

California State University, Long Beach

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This effort was performed under AFFTC contract numbers FA9300-05-M-3010 and FA9300-06-0009 with the Air Force Research Laboratory / Propulsion Directorate

Project Objectives

- Evaluate fast turn-around flight operations with a nanosat launch vehicle (NLV)-class prototype RLV
- Conduct two flights within a 24-hour period
- Pathfind operationally responsive spacelift (ORS) at a non-traditional launch site
- Refine requirements, concepts and processes for an operational reusable NLV
- Manifest technology experiments

Outline

- Project Objectives
- Introduction
- Prospector 7 Background and History
- Results and Discussion
- Summary and Conclusions
- Future Work

Introduction

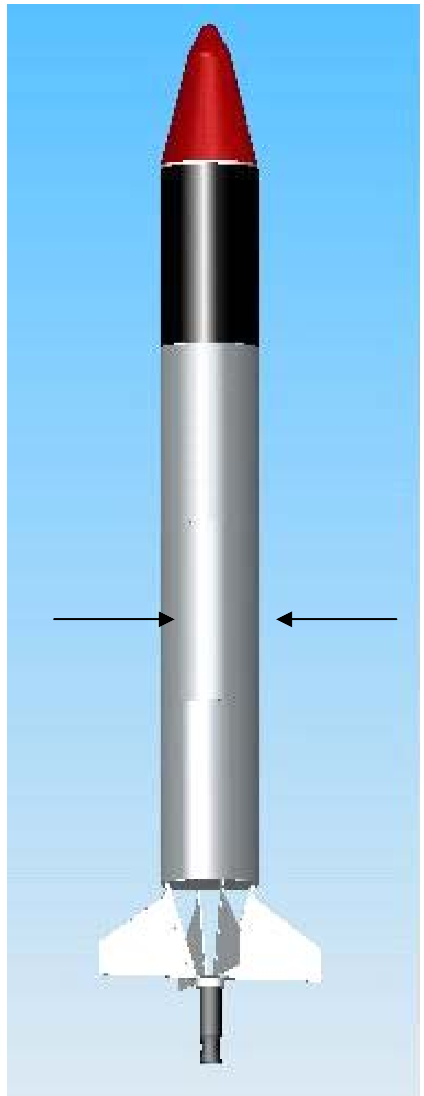
- AFRL/PR is sponsoring the GSC / CSULB team to develop and test prototype RLVs
- Focus on NLV-class mission
  - long term goal is 10 kg to LEO
  - “hybrid” configuration (reusable first stage, expendable second stage)
- SMC is utilizing the resulting vehicles to conduct ORS-oriented demonstrations
- Four flights in eleven months with a single test vehicle

P-7 Vehicle Elements

- initially trade performance for cost, schedule -

Fairing

Interstage



692 centimeters [272.5 inches]

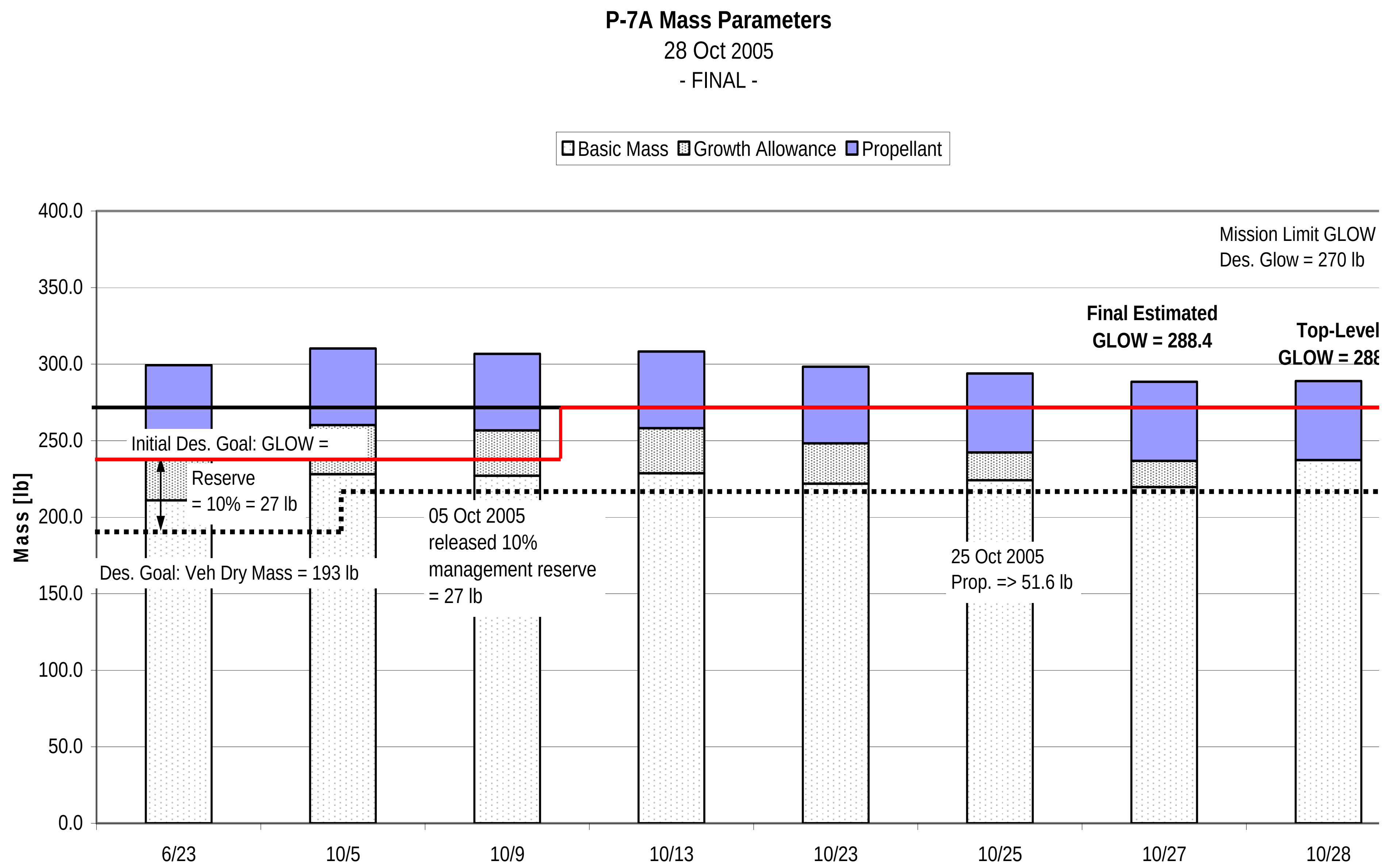
65 centimeters [26 inches]

First Stage

Thrust Structure

Engine

GLOW = 290 lbm


P-7A Mass Parameters
28 Oct 2005
- FINAL -
Basic Mass
Growth Allowance
Propellant
Mass [lb]
400.0
350.0
300.0
250.0
200.0
150.0
100.0
50.0
0.0
6/23
10/5
10/9
10/13
10/23
10/25
10/27
10/28
Mission Limit GLOW
Des. Glow = 270 lb
Final Estimated
GLOW = 288.4
Top-Level
Initial Des. Goal: GLOW =
Reserve
= 10% = 27 lb
Des. Goal: Veh Dry Mass = 193 lb
05 Oct 2005
released 10%
management reserve
= 27 lb
25 Oct 2005
Prop. => 51.6 lb

Prospector 7A / B: RLV Fast Turn-Around Operations

Garvey Spacecraft Corporation

California State University, Long Beach

- 6 month development cycle
- October 2005 flights
- LOX/ethanol propulsion
- Featured “refurbishable” elements
- 5,000 ft operational ceiling
- Payloads from MSU and Cal Poly SLO
- RLV operational metrics:
  - 18 hours of field prep.
  - 2 flights in 3.5 hours

Preparations Underway for Second Launch

Recovery Featured Parachutes and Replaceable Front End

Garvey Spacecraft Corporation

California State University, Long Beach

DirecWay Satellite Internet Station

P-7C: Launch Hardware Tracker Experiment

Garvey Spacecraft Corporation

California State University, Long Beach

- RLV flight sponsored by the payload provider (The Aerospace Corporation)
- April 2006
- Early evaluation test of Re-entry Break-up Recorder (REBR) concept
- Assessed GPS and Iridium data links
- Also served as pathfinder of ORS for SMC GALT initiative
- Fourth flight for MSU data logger

P-7D:
ORS Pathfinder Flight at San Nicolas Island

- AF decision to proceed:
  - 30 June 2006
- First delivery of major hardware:
  - 19 Sep 2006
- Advance Team Arrival:
  - 26 Sep 2006
- Launch:
  - 28 Sep 2006
- Team Departure:
  - 29 Sep 2006

- LESS THAN 3 MONTHS -

Results and Discussion

The P-7 Required a Lower Percentage of Component Replacement by Mass After the First Flight Than Had Been Predicted

Baselined Components Requiring Replacement	**Baselined Mass of Replaced Components** [kg / lbm]	**Actual Mass of Replaced Components** [kg / lbm]	**Components Actually Requiring Replacement**
engine (except pintle injector element, which is reused)	4.5 / 9.9	4.5 / 9.9	engine
fins (x2)	3.0 / 6.6	1.5 / 3.3	fins (x1)*
thrust structure struts (x2) (brackets not included)	0.7 / 1.6	0.4 / 0.8	struts (x1)
		0.7 / 1.5	first stage forward mating ring
interstage	8.5 / 18.7	8.5 / 18.7	interstage*
payload fairing	3.0 / 6.6	3.0 / 6.6	payload fairing*
TOTAL =	**19.7 / 43.4** **18.3% of final dry mass estimate****	**18.6 / 40.0** **16.9% of final dry mass estimate****	

* *these components were actually reused on subsequent flights, giving a final expended mass of 4.8% for this flight*

** *final vehicle dry mass estimate, with payloads, was 237.3 lb*

Turn-around Times Surpassed Baseline Estimate

	Local Time [h:min]	Elapsed Time After Start of Recovery and Turn Around Ops [h:min]	Task Duration [h:min]	Pre-Launch Estimated Duration [h:min]	Active Personnel	Estimated Manhours
P-7A launch	12:25					
P-7A landing	12:27					
P-7A POST-LANDING						
post-landing recovery ops - start	**12:27**		0:22	1:00	2	2:00
post-landing recovery ops - completed	12:49	0:22				
vehicle return to launch site - start	12:49	0:22	0:10	0:30	4	2:00
vehicle return to launch site - completed	12:59	0:32				
P-7A/7B REFURBISHMENT						
vehicle inspection, refurbishment and conversion to P-7B configuration - start	12:59	0:32	1:18*	1:15	8	10:00
vehicle inspection, refurbishment and conversion to P-7B configuration - completed*	14:17	1:50				
Flight Readiness Review - start	14:17	1:50	0:03	0:15	8	2:00
Flight Readiness Review - completed	14:20	1:53				
P-7 LAUNCH OPS						
load, prep vehicle on launch rail - start	14:20	1:53	1:01*	0:30	8	4:00
load, prep vehicle on launch rail - completed*	15:21	2:54				
ethanol loading - start	15:21	2:54	0:09	0:30	4	2:00
ethanol loading - completed	15:30	3:03				
LOX loading - start	15:30	3:03	0:15			
LOX loading - completed	15:45	3:18				
Conduct air and ground safety check; enter terminal count	15:45	3:18	0:08	0:15	4	1:00
P-7B launch	15:53	**3:26**	**3:26**	**4:15**		**23:00**
P-7B landing	15:33					

Summary and Conclusions

- Reducing the scale of prototype RLVs is enabling low-cost, near-term flight testing
- Operational transformation at least as important for RLVs as advanced technologies
- Already producing useful metrics
- The nanosat payload community is already benefiting from the expanded number of manifest opportunities

Future RLV Work

- Now developing the next generation Prospector 9 (P-9)
  - full-scale engine, propellant tanks, tank pressurization and thrust vector control
  - P-9A/B (no pressurization or TVC) will be used for enhanced RLV fast turn-around testing
  - P-9X will be used for high altitude (20 to 50 mi) ORS flight test at SNI
- Upgrading previous P-6 into the P-8 for interim flight testing

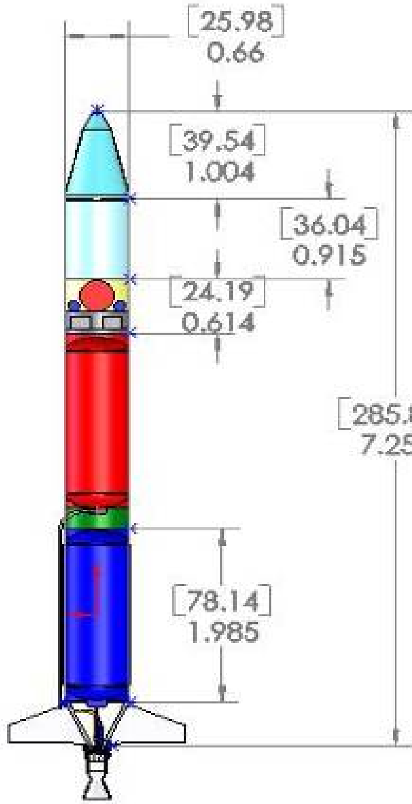
P-7D, P-9A/B, P-9X & NLV vehicles

(approximately to scale)

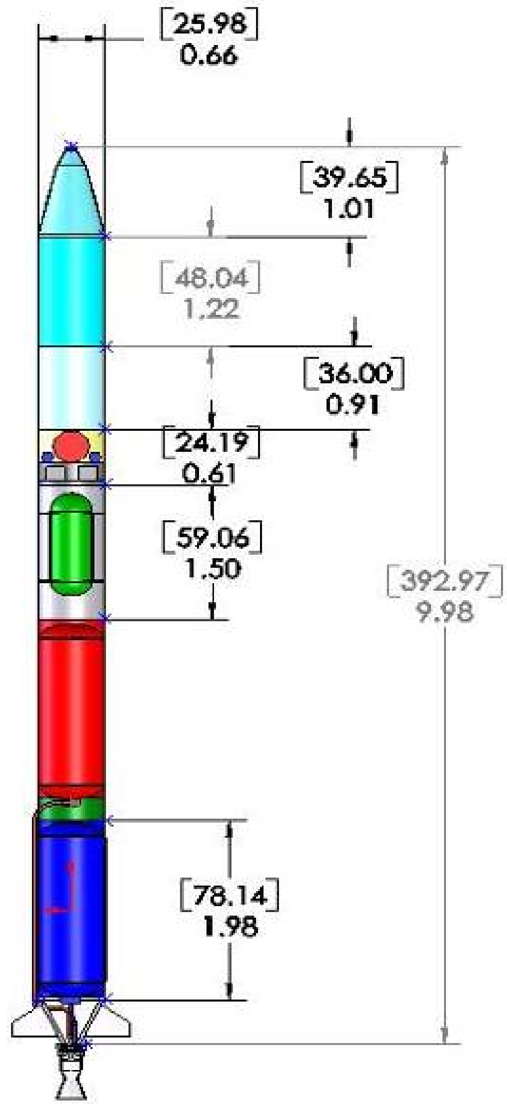
Garvey Spacecraft Corporation

California State University, Long Beach

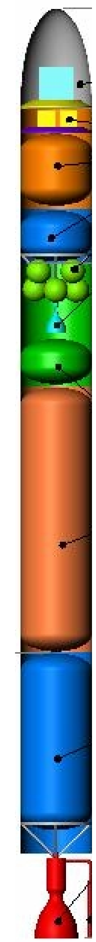
P-7D



P-9A/B



P-9X



NLV

First 4.5K Engine Test